

DISTRIBUTION OF GLACIOFLUVIAL SEDIMENT WITHIN AND ON THE SURFACE OF A HIGH ARCTIC VALLEY GLACIER: MARTHABREEN, SVALBARD

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ABSTRACT

Marthabreen is a 7.8 km long valley glacier in SW Spitsbergen. The glacier is partially covered by a layer of angular debris derived from rockfall in its accumulation area, pierced in places by pinnacles and ridges of glaciofluvial sediment. These concentrations of glaciofluvial sediment fall into three categories: (1) debris pinnacles; (2) longitudinal sediment dykes; (3) longitudinal ridge accumulations. Debris pinnacles are slabs of sediment (predominantly sands, gravels and cobbles) elevated to the glacier surface along thrusts. Longitudinal sediment dykes are low (< 0.5 m high) ridges of debris melting out of vertical sediment dykes within the body of the glacier. They are composed of a range of facies including sands, granule gravels, pebble gravels and diamicton. These dykes are sub-parallel to the longitudinal foliation on the glacier and form during folding of the stratification. Longitudinal ridge accumulations are higher (> 1 m high) ridges of sorted sand and gravels which are not associated with penetrative ice structures. Their occurrence downglacier of sediment dykes and debris pinnacles suggests that they originate as supraglacial or englacial channels or tunnels filled by sediment derived from the dykes or thrusts. The presence of large quantities of glaciofluvial sediment on the surface of Marthabreen does not imply englacial water flow at high levels within the glacier, but is related to ice deformational processes such as thrusting and folding of debris-rich stratification. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS glaciofluvial sediment; structural glaciology; thrusts; longitudinal foliation; debris entrainment; Svalbard

INTRODUCTION

The aim of this paper is to describe the mechanisms of entrainment, transport and release of glaciofluvial sediment at the high arctic valley glacier Marthabreen (Svalbard), and to outline the ice-deformational processes that determine the distribution of glaciofluvial material in the glacier. The Svalbard archipelago (77°N to 80°N) is currently 60 per cent glacierized (Hagen *et al.*, 1993), with an estimated 35 per cent of these glaciers being surge-type (Hamilton and Dowdeswell, 1996). Many of the glaciers in this region are polythermal, with extensive areas of temperate ice beneath their accumulation areas, but with their termini frozen to the bed (Hagen *et al.*, 1991; Ødegård *et al.*, 1992; Björnsson *et al.*, 1996).

The debris structure of polythermal glaciers is relatively poorly understood in comparison to that of temperate glaciers (Weertman, 1961; Swinzow, 1962; Boulton, 1970, 1978; Hooke, 1973; Clapperton, 1975; Hambrey and Müller, 1978). Recent work has helped refine this picture of debris structure within polythermal glaciers and has reaffirmed the importance of thrusting in elevating basal debris within them (Bennett *et al.*, 1996a; Hambrey and Huddart, 1995; Hambrey *et al.*, 1996; Murray *et al.*, 1997). The significance of the folding of debris-rich stratification in organizing both supraglacial and basal debris has also been highlighted (Hambrey and Dowdeswell, 1997; Glasser *et al.*, 1998; Hambrey *et al.*, 1998). The distribution and significance of glaciofluvial sediment within polythermal glaciers remains unclear (Bamber, 1989; Hagen and Saetrang, 1991; Hagen *et al.*, 1991; Vatne *et al.*, 1996; Hodgkins, 1997). Glaciofluvial material is found on the surface of both temperate and polythermal glaciers, where it

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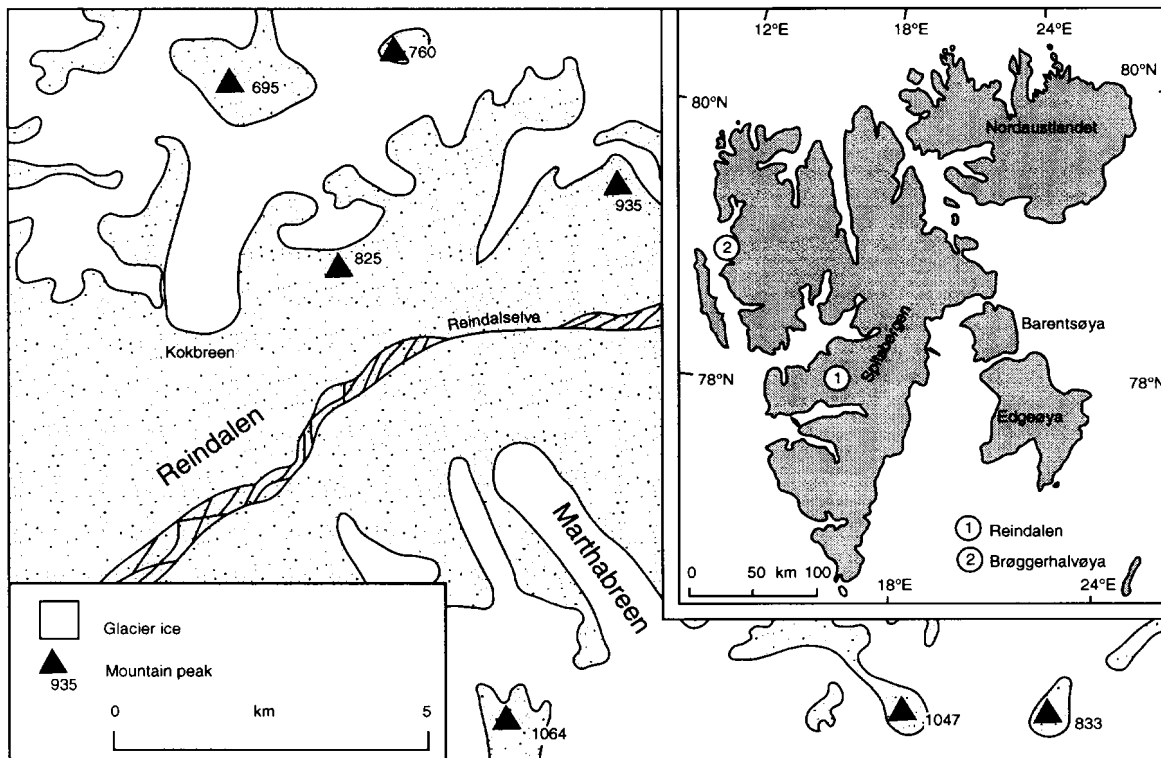


Figure 1. The location of Marthabreen and Reindalen in Svalbard

commonly occurs as ridges of sorted sands and gravels attributed to the melt-out of either subglacial or supraglacial/englacial channel or tunnel systems (Price, 1966, 1969; Boulton and Van der Meer, 1989). In temperate glaciers, unusually large surface volumes of glaciofluvial sediment have been attributed to fluvial transport at high elevations within the glacier basin (Kirkbride and Spedding, 1996; Näslund and Hassinen, 1996). Glaciofluvial sediment can also be transported to the surface of temperate glaciers by the upward-directed component of ice flow or along shear planes (Krüger, 1994). The large volume of glaciofluvial sediment on the surface of Marthabreen makes it an ideal location to study the debris structure and distribution of glaciofluvial sediment in a polythermal glacier and the possible links to glacier hydrology.

MARTHABREEN: THE STUDY AREA AND DATA ACQUISITION

Marthabreen (latitude 78°06'N, longitude 16°43'E; glacier number 136 13 of Hagen *et al.*, 1993) is a 7.8 km long valley glacier flowing into the ice-free valley Reindalen in SW Spitsbergen (Figure 1). The glacier is fed from a group of large cirques with a maximum elevation of 1050 m above sea level and currently terminates at an altitude of 240 m above sea level (Hagen *et al.*, 1993). In common with most Svalbard glaciers, Marthabreen has been in recession since early this century and its ice front is now stationary (Etzelmüller and Sollid, 1996). Aerial photographs from 1971 (Norsk Polarinstitut; Photograph S71 6051) show the glacier to have a steep front, although today the gradient of the snout is less than 11°. Marthabreen is reputed to have surged *c.* 1925 (Hagen *et al.*, 1993), but there is no evidence in the form of elevated trimlines or looped moraines to suggest that its advanced position in 1925 and its steep front in 1970 were anything other than a normal response to climatic trends. By analogy with other similar valley glaciers in Svalbard it is likely that Marthabreen is polythermal in nature (Hagen *et al.*,

1991; Hagen and Saetrang, 1991; Ødegård *et al.*, 1992). Evidence for this is the presence of Aufeis below the glacier snout, whilst frosted walls in a drainage tunnel near the snout also confirm that the ice at its margins is cold.

The surface of the glacier has a thin, but laterally extensive, supraglacial debris layer. This includes one very prominent and several much smaller medial moraines composed exclusively of supraglacial debris, and numerous much smaller dirt cones and linear ridges of more varied debris content at the eastern margin. Observations on debris-free parts of the ice surface show evidence for three types of planar structure in the glacier: (1) folded stratification forming a distinct longitudinal foliation parallel to glacier flow; (2) thrust faults developed transverse to ice flow; and (3) crevasse traces. The longitudinal foliation on Marthabreen is orientated parallel or sub-parallel to glacier flow (140–320°). The foliation is not linear but has a low-amplitude sinuosity, typically dipping at steep angles of between 70 and 85°. As on other glaciers, the longitudinal foliation is visible on the glacier surface as intercalated layers of coarse-bubbly, coarse-clear and fine ice (Allen *et al.*, 1960). The surface of the glacier is crossed by a series of fractures inferred to be thrusts, orientated approximately transverse or diagonal to glacier flow, and dipping upglacier at angles in excess of 40°. Some of these thrusts contain little or no debris, whilst others contain significant quantities of sand and gravel. Crevasse traces, extending back from the snout into the upper accumulation basin, are also visible on the surface of Marthabreen.

Glaciofluvial sediment on the glacier surface is associated with both pinnacles and longitudinal ridges. Twelve pinnacles and ridges on the glacier surface were excavated and washed clean of debris to reveal their association with the ice structures beneath. The length, breadth and height of each feature was measured in the field, and profiles were constructed using an Abney level and tape. Sedimentary descriptions consist of sedimentary logs, clast shape analysis and maximum *b*-axis determinations of 50 clasts. Clast shape was based on the method of Benn and Ballantyne (1994) as modified by Bennett *et al.* (1997) using samples of 50 fine-grained sandstone clasts.

DEBRIS STRUCTURES ON MARTHABREEN: OBSERVATIONS

A traverse from the clean ice of Marthabreen in the south, through the ice-cored moraine complex that marks the terminus of the glacier, to the proglacial sandur in the north shows that the glacier can be divided into three zones (Figure 2). Zone One is the area around the present ice margin where there is a thick (1.5 to 3.5 m) and continuous layer of angular debris over a core of buried ice. Glacier ice is revealed within several water-filled kettleholes. Upglacier of this angular debris cover, Zone Two consists of a buried ice surface with a thinner debris layer (0.5 to 1.0 m thick). This zone is composed of a complex mixture of sedimentary facies where angular boulder debris is juxtaposed with rounded gravels and diamicton. A group of prominent debris pinnacles (5 to 15 m high) dominates this zone. These pinnacles have triangular-shaped ramps on their upglacier sides, with steep and actively backwasting downglacier faces. The upglacier ramps typically consist of a slab of sediment overlying buried ice, and dip upglacier at angles of between 15 and 37°.

Upglacier of Zone Two, the debris cover thins and the surface gradient increases to approximately 11° in Zone Three (Figure 2). Here the glacier surface is either debris-free or covered to the depth of a single clast by angular pebble/cobble gravel. The surface is broken by a series of ridges and cones composed of well-sorted sand and gravel units of glaciofluvial origin. Three types of debris-rich structure were observed on the glacier surface in this area: (1) debris pinnacles; (2) longitudinal sediment dykes; and (3) longitudinal ridge accumulations. The characteristics of each of these are described below, together with the resultant supraglacial facies.

Debris pinnacles

Four examples of debris pinnacles were examined on the glacier surface. The first debris pinnacle (Figure 2B) consists of a spire 3.5 m high, 2 m wide (transverse to flow) and 5 m long (parallel to flow). It

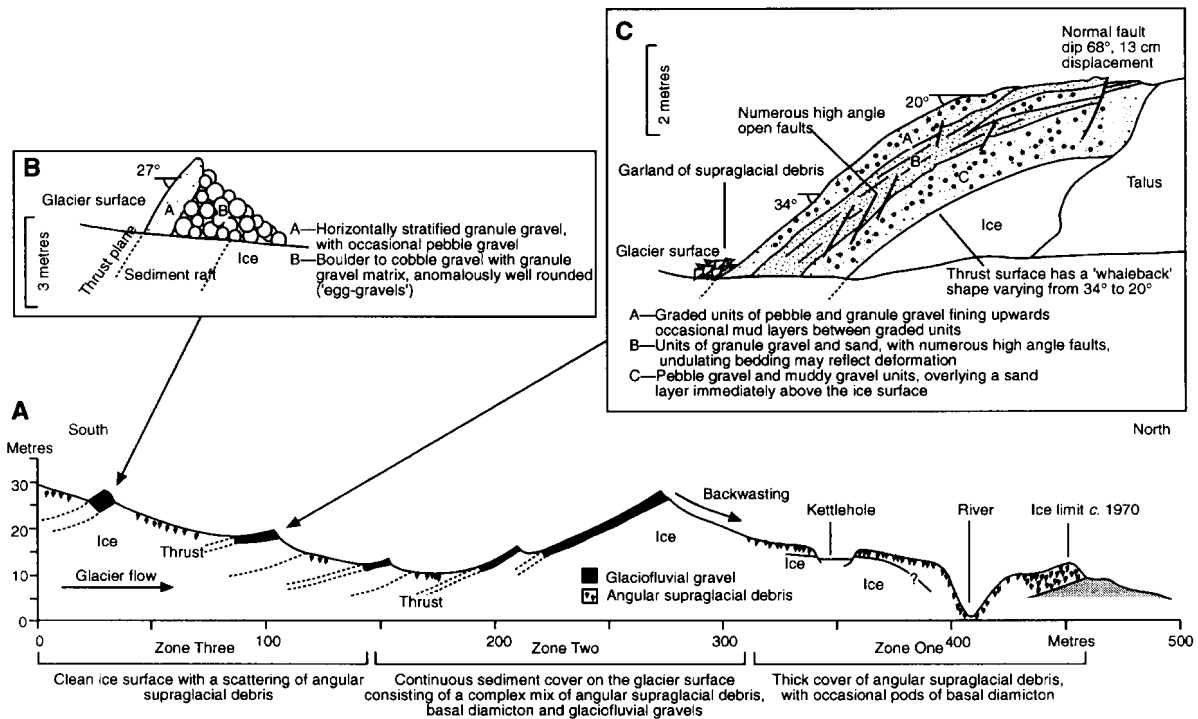


Figure 2. (A) Cross-section through the ice-marginal area of Marthabreen. Insets (B) and (C) show details of the sedimentology of two debris pinnacles

is composed of a central spine of granule gravel with occasional pebble clasts (maximum thickness 0.55 m) resting on a unit of boulder and cobble gravel in which the clasts show a remarkable degree of roundness (Figure 3, Figure 4A). A core of buried ice is inferred, but was not observed. The sediment units dip upglacier at 27° and penetrate the glacier surface as a single slab along a fracture. By analogy with similar structures elsewhere in Svalbard, this feature is interpreted as a thrust (Hambrey *et al.*, 1996, 1997; Glasser *et al.*, 1998). The second example is a 3 m high triangular mound, 4.5 m wide at its base, composed of a slab of sand and gravel overlying a core of buried ice (Figure 2C). On either side of this triangular ramp the mound is actively backwasting. The sediment slab is approximately 0.75 m thick and penetrates the glacier at 35° along a prominent fracture. Offset stratification and two closed fractures either side of the prominent fracture suggest that this feature is also a thrust. The buried ice core has a whaleback form (Figure 2C). The sediment slab consists of three units of granule and pebble gravel with some minor sand layers. Numerous high-angle (65 to 68°) normal faults with upglacier throws of between 0.05 and 0.15 m interrupt the bedding (Figure 2C). The surface of the triangular ramp contains a veneer of supraglacial debris that forms a distinct garland around the upglacier base of the mound. The third and fourth examples also appear to be organized along a thrust and are morphologically and sedimentologically similar to those described above.

Longitudinal sediment dykes

These longitudinal ridges (trending south to north) are composed of sand and gravel. They range in height from a few centimetres to several metres and in length from as little as a metre to over 60 m. These ridges can be divided into two groups on the basis of size: low ridges less than 0.5 m high and higher ridges in excess of 1 m high. On washing the glacier surface free of debris, these two groups are easily

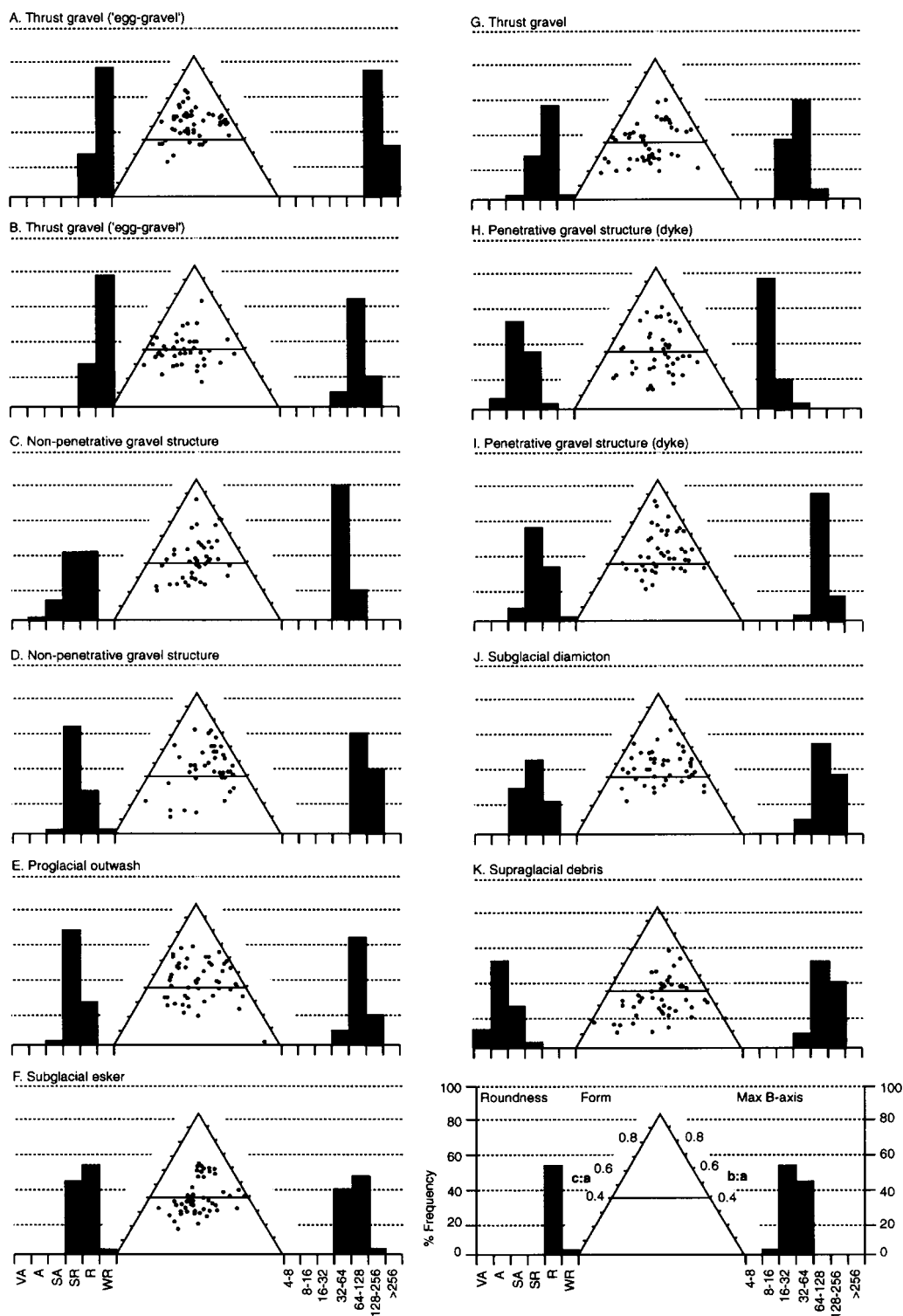


Figure 3. Clast shape and maximum *b*-axis data for the various facies found within the Marthabreen terminus

(a)



(b)



Figure 4. Photographs of Marthabreen. (A) Debris pinnacle containing anomalously rounded gravels ('egg gravels'). (B) Typical sediment dyke on the surface of Marthabreen. (C) Longitudinal ridge accumulation with *in situ* sediment situated on top of a ridge of ice containing no visible ice structures

(c)



Figure 4 – continued

distinguished since the low ridges are associated with dyke-like ice debris structures (longitudinal sediment dykes), while the larger ridges do not penetrate the glacier surface (longitudinal ridge accumulations; see below).

Three examples of longitudinal sediment dykes were examined in detail. The first example consists of a 6 m long ice ridge which is 0.5 to 1.0 m high and protected by a blanket of coarse sand and granule gravel derived from the melt out of a central sediment dyke (Figures 4B and 5A). The sediment dyke varies in width from 0.05 to 0.14 m and is sub-parallel to the foliation. The sediment fill consists of fine sand and granule gravel (Figure 3). These graded units dip at 20° downglacier along the central axis of the dyke and in some locations are also intensely folded in the form of isoclinal folds. In several places the dyke is completely closed and the sediment fill is pinched out by the ice walls. At the upglacier and downglacier ends of the dyke the sediment fill stops abruptly, although the structure can be traced further as a closed and debris-free ice fracture. The glacier ice adjacent to the sediment dyke is cut by two intersecting fractures, both containing disseminated mud clots. The second and third longitudinal dykes are discontinuous chains of sediment exposed along a single ice fracture that can be traced over a distance of 25 m (Figure 5B,C). Individual sections of sediment dyke vary in length from as little as 0.25 m to over 8 m. The sediment dykes are typically only 0.05 to 0.15 m wide. Both the sediment dykes and the intervening ice fractures are folded along their long axis parallel to the foliation. The sediment dykes contain a range of structureless sand, granule gravel and pebble gravel (Figure 3).

Longitudinal ridge accumulations

In addition to those ridges centred on sediment dykes, a series of larger flow-parallel ridge accumulations also occur on the glacier surface. These ridges are between 20 and 30 m long and 1 to 3 m high (Figure 4C). Each ridge is crested by *in situ* sand and gravel, while the ridge flanks contain slumped debris. Two types of contact between the *in situ* sediment and glacier ice were observed. First, the sediment may lie above a flat or gently convex ice surface where no fractures are observed within the underlying ice and the sediment pile appears to be independent of the glacier surface that it insulates. Second, the sediment may lie within a distinct semicircular channel between 0.1 and 0.5 m in diameter. Again, this appears to be unrelated to any ice structure, although it is sub-parallel to the foliation. The *in situ* sediment on the crest of these ice-cored ridges is between 0.2 and 0.6 m wide and in places is up to 1 m thick. Sedimentary facies include pebble and granule gravel units, some of which are organized into

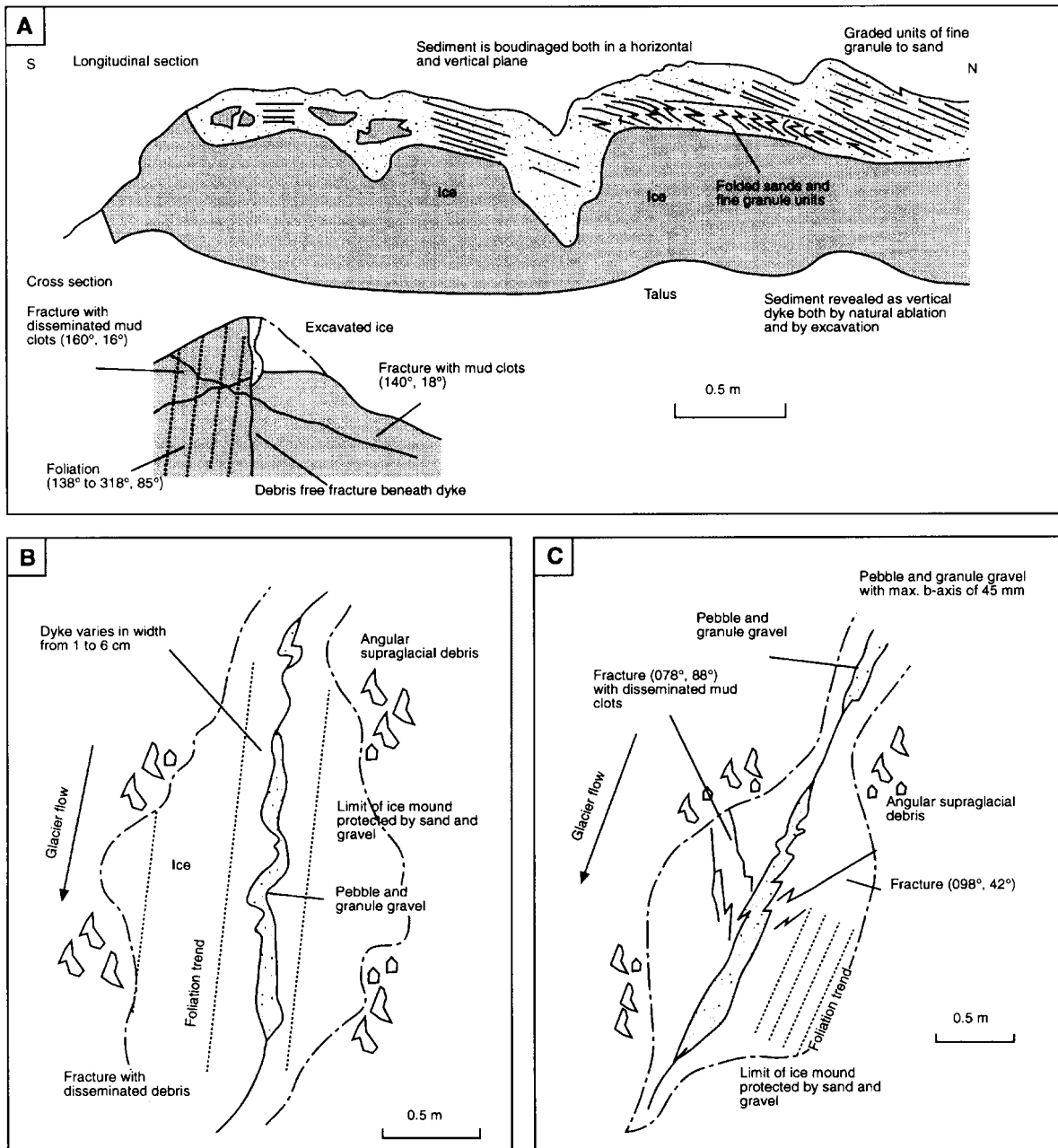


Figure 5. Scale sketches and plans of three sediment dykes. (A) Longitudinal and cross-sectional views of a sediment dyke. The cross-section is taken from the upglacier or southern end of the sediment dyke. (B) and (C) Plan views of two sediment dykes showing the folding and width variation of the sediment dyke

graded units but which are more commonly massive. Units of pebble gravel supported by a silt matrix were also observed. The bedding in these is either sub-horizontal or dips gently upglacier at between 3 and 5°. Clast shapes and *b*-axis dimension are very similar to the sand and gravel within the sediment dykes and debris pinnacles (Figure 3). These ice-cored sediment ridges are frequently located

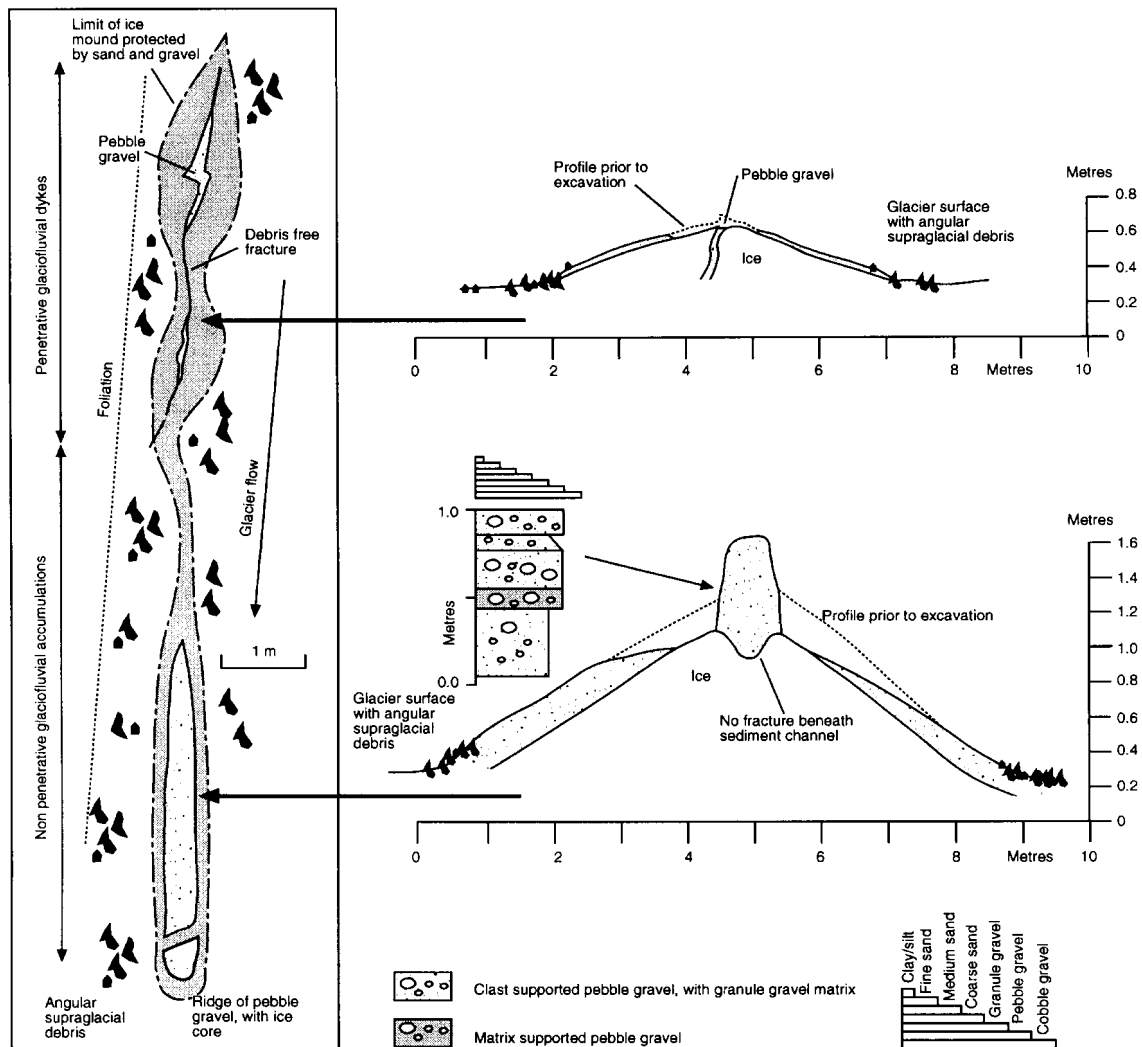


Figure 6. Scale plan showing the relationship of a sediment dyke to a longitudinal ridge accumulation

downstream of sediment dykes or debris pinnacles (Figure 6). In all examples, the upglacier ends of the ice-cored sediment ridges do not penetrate the glacier surface.

Sediment release

Degraded examples of all these debris ridges and pinnacles can be seen within Zone Two of the Marthabreen ice margin (Figure 2). In this zone there are also longitudinal sediment dykes which contain diamicton with striated and faceted clasts, suggesting that the dykes may be in contact with the glacier bed. Backwasting along the flanks of all the longitudinal ridges and from the front face of the debris pinnacles results in a complex association of sedimentary facies. Subglacially derived diamicton is juxtaposed with well-sorted gravels and angular cobble gravel. As the buried ice within the pinnacle is

removed by melting, a garland of angular cobbles and pebbles forms at its base. Consequently the supraglacial sediment on Marthabreen consists of irregular belts of angular debris. In plan, these describe irregular loops and swirls centred on a core of sorted sand, gravel or diamicton.

DEBRIS STRUCTURES ON MARTHABREEN: INTERPRETATION

Debris pinnacles

The simplest explanation for the debris pinnacles is that they are produced by thrusts that have entrained glaciofluvial sediment from the bed. Similar interpretations have been attached to surface accumulations of glaciofluvial sediment on temperate glaciers (Krüger, 1994). The debris pinnacles at Marthabreen develop wherever debris-rich thrusts melt out on the glacier surface and the sediment raft insulates the footwall from ablation (Hambrey *et al.*, 1996). The occurrence of several debris pinnacles along the outcrop of a single thrust suggests that sediment within the thrust is elevated to varying levels along its length. The reasons for this are unclear but may reflect lateral variations in the subglacial facies such as the rheology and thickness of the subglacial sediment pile. A fuller understanding of this requires greater knowledge of the mechanisms that are responsible for the elevation of subglacial sediment along thrusts.

Longitudinal sediment dykes

Debris structures sub-parallel to longitudinal foliation have been recognised in a number of studies (Shaw, 1980; Sharp, 1985; Bennett *et al.*, 1996a; Hambrey and Dowdeswell, 1997; Glasser *et al.*, 1998). Sharp (1985) described the occurrence of longitudinal ridges of glaciofluvial sediment parallel to foliation on Eyjabakkajökull, Iceland, and attributed these to the meltout of englacial channel fills. Kirkbride and Spedding (1996) explained similar accumulations of glaciofluvial sediment near the surface of certain Icelandic glaciers in terms of water and sediment flow within high-level conduits. Bennett *et al.* (1996a) described foliation-parallel sediment dykes on Svalbard glaciers, interpreted as deformed supraglacial channels. Hambrey (1977) demonstrated that on some Norwegian glaciers supraglacial meltwater channels form sub-parallel to longitudinal foliation and that glaciofluvial sediment accumulates in these channels if they become choked with sediment elevated to the glacier surface by thrusts, or by the accumulation of surface rockfall debris. During continued glacier flow these channels may become compressed normal to flow to form boudinaged lenses (Bennett *et al.*, 1996a).

Finally, Glasser *et al.* (1998) argued that basal sediment within a glacier may be elevated parallel to the foliation by folding of stratification during flow compression to form 'foliation-parallel ridges'. This type of folding may elevate not only the basal ice layer but also deformable sediment from the glacier bed (Lawson *et al.*, 1994; Hambrey *et al.*, 1998). This implies that the décollement surface need not necessarily occur at the ice-sediment interface but may be located within the basal sediment itself (Glasser *et al.*, 1998). Compression transverse to flow may arise in any glacier where a broad accumulation area feeds a narrow and confined glacier tongue (Figure 7A), and it is suggested that this type of ice deformation best explains the longitudinal sediment dykes on the surface of Marthabreen. Since the longitudinal sediment dykes on Marthabreen are dominated by glaciofluvial facies, and not by the elevation of diamicton, they are not true 'foliation-parallel ridges' (Glasser *et al.*, 1998). Instead, the sediment dykes are produced by the deformation of supraglacial channels and englacial conduits (and occasionally by the elevation of basal sediment) during folding of the stratification (Figure 7B,C).

Longitudinal ridge accumulations

The larger ice-cored sand and gravel ridges all occur downglacier of either longitudinal sediment dykes or debris pinnacles. Since the contact with glacier ice beneath these sediment accumulations often

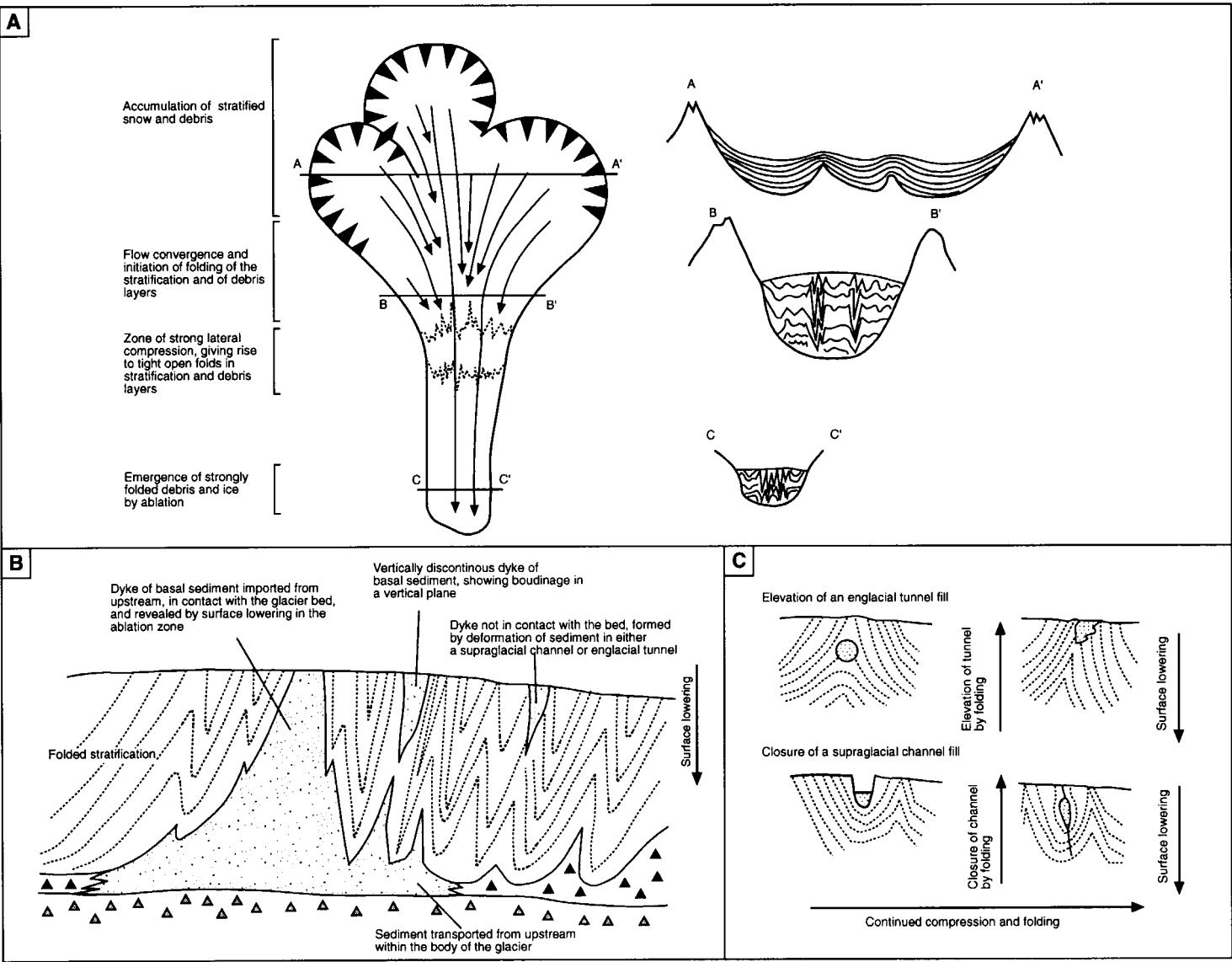


Figure 7. (A) Folding of stratification by transverse compression within a glacier tongue (modified from Hambrey *et al.*, 1998). (B) and (C) The effects of this folding on the distribution of englacial and supraglacial sediment within the ice

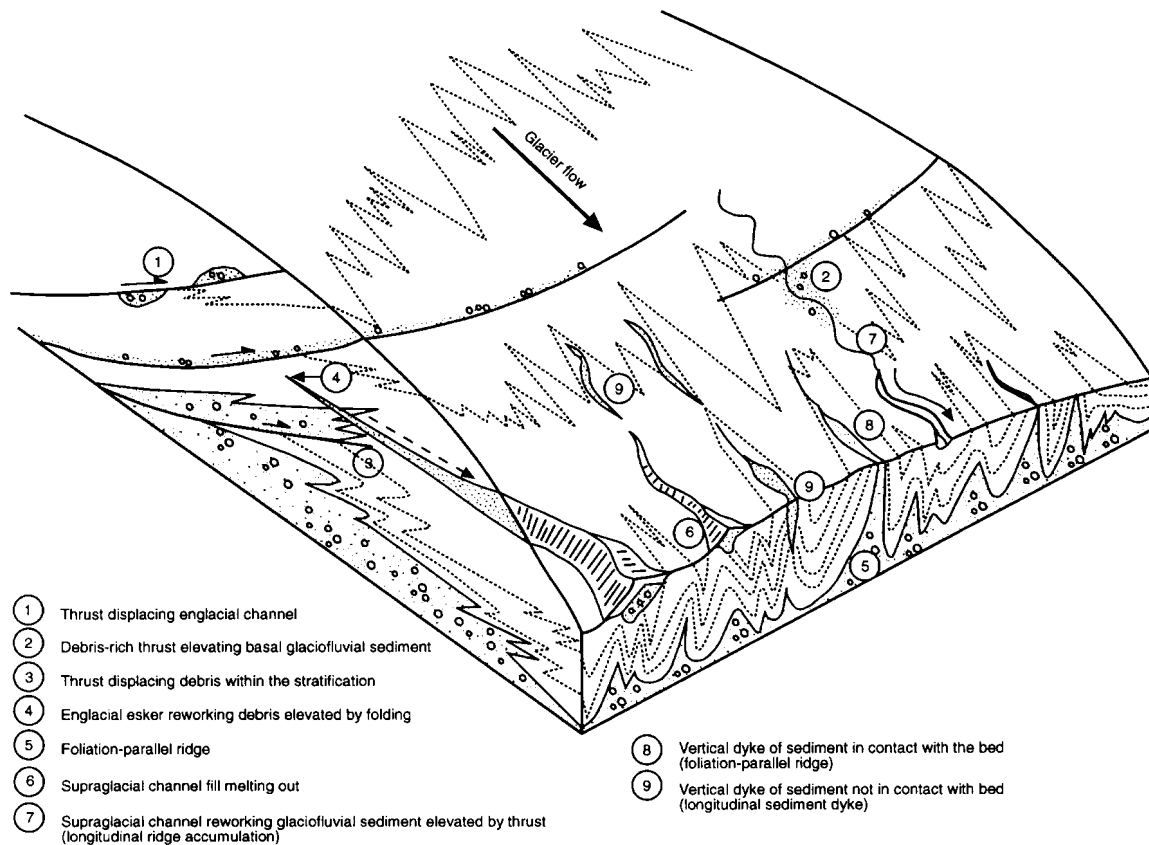


Figure 8. Summary block diagram of the debris structure of the terminal zone of Marthabreen

has a channel form, it is suggested that these represent supraglacial channels or englacial conduits filled by sediment derived from dykes or thrusts. In this model, conduits or supraglacial channels intersect debris-rich structures and quickly become choked by the additional sediment. This process occurs close to the current glacier margin so these channels are not subsequently deformed into longitudinal sediment dykes.

DISCUSSION

The distribution of glaciofluvial sediment and hydrological inferences

Glaciofluvial sediment is elevated to the surface of Marthabreen by three mechanisms: along thrusts, by folding of stratification transverse to flow, and in supraglacial ridges (Figure 8). The presence of glaciofluvial sediment on the glacier surface does not require englacial water flow at high levels within the glacier basin as suggested by Kirkbride and Spedding (1996) and by Näslund and Hassinen (1996). Instead, the role of structural attributes (including thrusting and the folding of stratification to produce longitudinal foliation) is more important in determining the manner in which glaciofluvial sediment is distributed within polythermal valley glaciers. The implication is that there is need for caution in inferring glacier hydrology simply from the distribution of glaciofluvial sediment on the surface of a glacier (Krüger, 1994).

Facies mixing

The elevation of basal and glaciofluvial material in thrusts and flow-parallel structures is an important component of the supraglacial debris load of Marthabreen. Consequently, in many locations on the glacier surface angular rockfall material is juxtaposed with more rounded basal and glaciofluvial material, forming a complex facies association. The deposition of this sediment either as supraglacial meltout till or its resedimentation by debris flowage produces a heterogeneous sedimentary facies, with a diverse range of clast and grain-size characteristics. This adds to the range of mechanisms that are capable of producing facies mixing, and its recognition within Pleistocene glacial sediments may provide important palaeoglaciological inferences.

The formation of anomalously rounded gravels ('egg gravels')

Anomalously rounded gravels ('egg gravels') have been reported in glacial environments elsewhere in Svalbard, particularly on Brøggerhalvøya (Figure 1). They possess a greater roundness and sphericity than all other high arctic glacial facies, including those derived from subglacial eskers (Bennett *et al.*, 1997; Huddart *et al.*, 1998; Figure 4). Their interpretation is problematic, although their occurrence on Brøggerhalvøya has been attributed to the reworking of raised beach deposits from the last interglacial by valley glaciers (Bennett *et al.*, 1997; Huddart *et al.*, 1998). The anomalously rounded gravels at Marthabreen differ from those of Brøggerhalvøya since their altitude (*c.* 250 m a.s.l.) is well above the Weichselian marine limit on Brøggerhalvøya (45 m a.s.l.) (Forman and Miller, 1984; Forman *et al.*, 1987). Whilst there is little doubt that reworking of raised beach deposits could produce such anomalously rounded gravels on Brøggerhalvøya, as suggested by Huddart *et al.* (1998), an alternative explanation is required for those occurring at the higher altitudes on the surface of Marthabreen.

One possible explanation for these gravels is that they are formed where significant quantities of sediment-rich subglacial meltwater rise along thrusts in the glacier (Figure 9). Since thrusts are of a limited aperture, only particles below a certain threshold diameter are transported up into the glacier. Particles above this threshold diameter are trapped at the base of the thrust and may be subjected to rapid abrasion by the passage of water and abrasive particles. If there is an infinite and continual supply of fresh, fine-grained material to this system as meltwater is flushed along the thrust, together with a constant supply of fresh abrasive particles, the trapped particles may become exceptionally rounded. As the thrust melts out, the trapped particles are exposed as a lag deposit consisting of anomalously rounded and sorted gravels at its base. Alternatively, further thrust displacement may elevate the 'egg gravels' along the thrust plane. This hypothesis requires water flow along thrusts, at the interface between warm interior ice and the cold marginal zone. This is plausible where thrusts form due to flow compression across the thermal boundary (Boulton, 1972). There is also strong evidence for the outflow of water along thrusts on certain Svalbard polythermal glaciers (Hagen *et al.*, 1991), lending hydrological credibility to this hypothesis. It is possible to speculate that this type of situation may be commonplace in polythermal glaciers where thrusting occurs at the thermal boundary between warm and cold ice, raising the intriguing possibility that anomalously rounded gravels and cobbles are indicative of polythermal glaciers. Further observations from a range of glacial environments are, however, required to corroborate this statement.

CONCLUSIONS

1. At Marthabreen there is evidence that three processes operate to produce accumulations of glaciofluvial sediment on the glacier surface: thrusting, folding and the filling of englacial or supraglacial channels and tunnels.
2. Debris pinnacles on the glacier surface are produced where slabs of sediment are elevated along thrust faults, while the folding of sediment parallel to the longitudinal foliation produces longitudinal sediment dykes. Longitudinal ridge accumulations are produced downstream of these features where

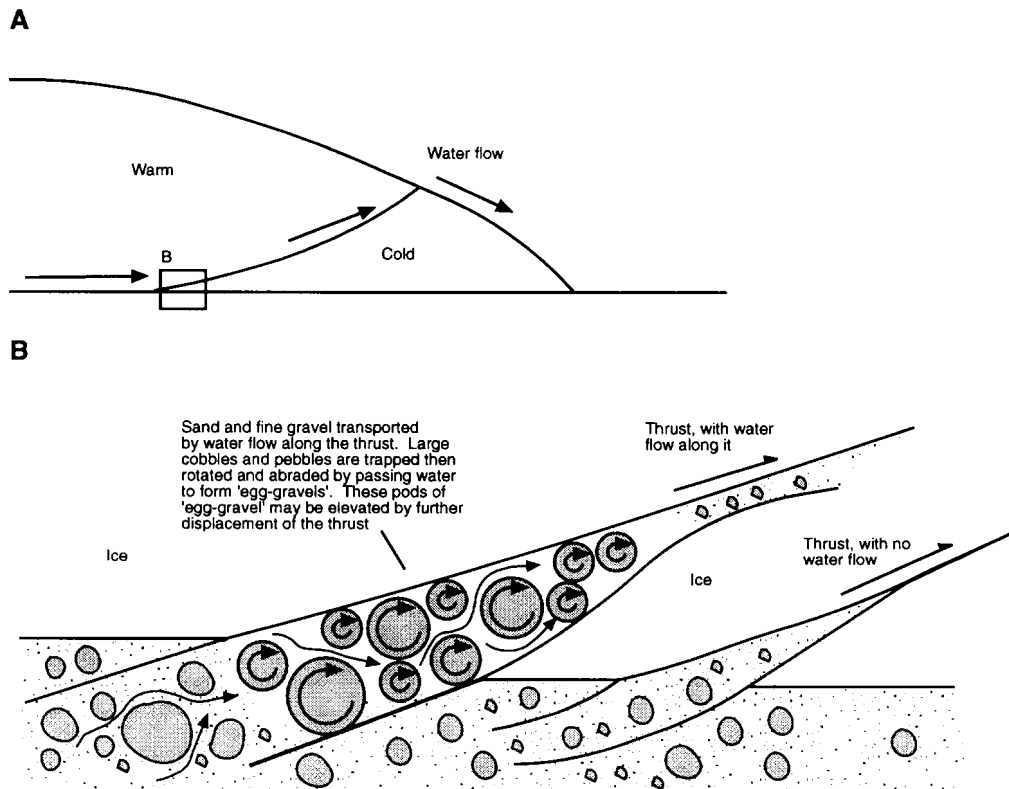


Figure 9. A model for the formation of anomalously rounded gravels ('egg gravels') in glacial environments

sediment is reworked by englacial or supraglacial streams.

3. The presence of large quantities of glaciofluvial sediment on the surface of a glacier need not imply the existence of englacial water conduits at high levels since ice-deformational processes, such as thrusting and folding, are also capable of elevating this material. These processes strongly influence the distribution of glaciofluvial sediment within polythermal glaciers.
4. A complex supraglacial facies is produced in areas where glaciofluvial material from thrusts or foliation breaks the ice surface and mixes with the angular rockfall material.
5. There is evidence in the form of mud clots that water previously flowed along closed fractures at Marthabreen. This suggests that sediment-rich water is an important agent in fracture propagation in polythermal glaciers, although this topic deserves further attention.
6. Pods of anomalously rounded gravels ('egg gravels') are formed where large volumes of sediment-rich subglacial meltwater rise along thrusts in the glacier. Clusters of anomalously rounded gravels and cobbles may be diagnostic of polythermal glaciers.

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